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Absorption and transmission of boundary layer noise through flexible multi-layer micro-perforated structures

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ABSTRACT

This paper describes analytical and experimental studies conducted to understand both the absorption and transmission performance of non-fibrous micro-perforated partitions excited by a turbulent boundary layer (TBL). This is of relevance in surface and air transport systems for the airframe design of external liners. A fully-coupled modal formulation is established that predicts the absorption coefficient and the transmission loss (TL) of finite-sized and infinite-sized partitions made up of a micro-perforated panel (MPP) backed by an air cavity and a thin plate. The front MPP undergoes random wall-pressure fluctuations with prescribed auto- and cross- correlation properties such as a TBL and/or an acoustic diffuse field (ADF). An experimental methodology is proposed to evaluate in a closed wind tunnel both the absorption and insulation performance of a TBL-excited MPP partition. This leads to an approximation of the frequency-averaged power flow injected by the TBL into the MPP partition. Both the predictions and the measurements show significant differences in the absorption and TL curves when considering either a low speed TBL or an ADF excitation. These properties are examined considering a weighted contribution of the acoustic and turbulent components, as it is the case for an aeroacoustic excitation. A hole-based transitional Strouhal number is found below which low-back scattering of the wall-pressures occurs and above which the MPP apertures efficiently convert turbulence into back-scattered sound whatever the magnitude of the acoustic component. As for the TL, a minute increase of the acoustic component generates most of the TL decrease. Finally, the effects of adding a second MPP within the cavity are assessed for both the absorption and the TL.

1. Introduction

One of the main challenges of air transport is to attenuate the environmental impact of air traffic despite its continuing expansion. Control efforts have been extensively focused on the airframe noise problems due to the introduction of the high bypass ducts and serrated nozzles, that have displaced the main contributor of noise from engines to airframe, especially

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during landing and approach conditions [1]. In addition, fuselage materials are being progressively substituted by carbon-fiber reinforced plastics with reduced critical frequencies. It implies a more efficient transmission of mid-frequency noise components through the aircraft sidewalls [2].

The problem of reducing the airframe noise, radiated outward or transmitted into the cabin, is complex. It involves a variety of conflicting constraints: it should not degrade the aircraft aerodynamic performance and should be robust to a wide range of wind speeds and turbulent inflow conditions. At an early stage, passive methods have been introduced due to their straight realisation. They provide significant noise reduction at high frequencies but also add additional weight and may obstruct fast routine maintenance inspection [3]. Several active flow control technologies have also been studied, such as plasma techniques [4], and air-blowing and suction [5]. These are promising techniques, but still at an early stage. Taking aviation safety and energy consumption into consideration, active flow control methods are mainly applied to downscaled model of airframe components and have a moderate technology readiness level. Active structural acoustic control and active vibration control have also been investigated for the reduction of the broadband noise induced by a turbulent boundary layer (TBL). Although significant reductions have been achieved in the transmitted sound power up to 500 Hz [6], these technologies require a large number of actuators and sensors when frequency increases. Also, random TBL noise cannot be controlled with standard feed-forward techniques. Feedback control systems are better suited since there is no time-advanced reference signals, the latter being correlated over length scales that exponentially decay with frequency [7].

To enhance absorption and avoid transmission of flow noise without the introduction of active or massive components, layouts of panels with slits or perforations have been considered as a non-fibrous alternative to conventional silencers in ducted configurations [8,9], even though knowledge about their acoustic behaviour in presence of grazing and/or bias flow is still ongoing research [10]. Back to 1972, Ffowcs Williams [11] developed a theoretical formulation to predict how the noise induced by a TBL is affected by the presence of an absorbent liner with a perforated facesheet. The interaction of the turbulence with a perforated screen may generate additional sound rather effectively due to scattering effects by the individual apertures. He treated the problem of broadband sound generation by considering a body of turbulence near an infinite, rigid, thin screen with circular perforations, assuming that the size of the apertures was much smaller than the distance between them and that the variations in pressure within the individual apertures were negligible. He found that the hydrodynamic pressures drive a fluctuating volume flow through the upper and lower surfaces of the screen apertures, constituting two equivalent and opposite monopole sources. The form of the net field is thus dependent on the acoustical properties of the screen. Acoustically transparent surfaces support aerodynamic dipoles while more ‘opaque’ surfaces have monopoles at the apertures that efficiently scatter the hydrodynamic pressures into sound. The monopole-type scattering occurs for surfaces with a low perforation ratio, e.g. $\sigma < < d_h M / l$, with d_h the holes diameter, M the free-stream Mach number and l the TBL convective length scale. $l/M \left(\approx 0.6\lambda\right)$ scales on the acoustic wavelength λ, which is much larger than l for a low-speed flow. This theoretical model was verified experimentally by Nelson [12], that showed that the equivalent source model was giving a predictive description of the sound produced by perforate facing materials for $\sigma \approx 9 - 43\%$ in terms of dipole characteristics, and was valid for arbitrary hole spacing. He determined the radiated sound power in the far field when an air jet impinged on perforated screens. Additional broadband and tonal sound was generated for values of the hole-based Strouhal number, $St_h = fd_h/U_\infty$, greater than 0.1, with f the frequency and U_∞ the flow free-stream velocity. The tonal peaks were attributed to a flow-excited resonance phenomenon due to a locking-in between the flow eddies in the perforations and either the cavity resonances or the duct modes near cut-on [13]. This feature is important for applications operating at high Strouhal numbers such as perforates in ventilation systems.

This subject has also been studied in more practical configurations such as in cylindrical geometries with applications to exhaust dissipative mufflers of internal combustion engines [8,10] and intake-lip or core-duct liners [9], with a view to educing the liner impedance under grazing and/or bias flow conditions. Aygün and Attenborough have compared the insertion loss (IL) of perforated and non-perforated poroelastic silencers mounted parallel to the streamlines of a low-speed flow [14]. They concluded that, whether the plate was perforated or not, increasing the mean air flow enhanced the IL at high frequencies and perforating the plate increased the IL at frequencies lower than 100 Hz. When the porous plate was mounted transversely across the flow duct [15], the IL increased when lowering the perforation ratio. Feng gradually varied the incidence angle of an unbacked perforated panel with respect to an open low speed flow [16]. The largest tone-like signal appeared at 75° incidence at a frequency in inverse proportion to the holes diameter, but the flow-induced sound stayed broadband at 0° or 90°.

Of interest is to explore the use of these devices when further reducing the size of the perforations, thereby increasing their acoustic resistance. These treatments are resonance absorbers composed of micro-perforated panels (MPPs) with sub-millimetric holes backed by an air cavity. MPP absorbers are alternative solutions for situations when porous components are excluded due, for instance, to the presence of high flow velocity or restrictions imposed by special hygienic conditions, such as in hospitals or in food industries. In addition, they can be made of recyclable materials constituting a non-polluting environmental option. One important property of backed MPPs is the fact that they are tuneable control devices. Optimal performance can be achieved by a proper selection of their physical constitutive parameters, such as the panel thickness, the size and shape of the perforations, the perforation ratio and the cavity depth. The goal is to increase the viscous losses through the apertures that dissipate the acoustic energy around the Helmholtz resonance and to obtain high absorption values over a broad bandwidth [17,18]. Their advantages come from the fact that they are light compact devices that can be fitted in the small spaces available, for instance within aircraft sidewalls. They can easily be cleaned and maintained, are not flammable and can be manufactured with composite or bio-inspired materials, constituting then favorable options to use in

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